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PERFORMANCE ESTIMATION FOR HIGHLY LOADED SIX AND TEN BLADE PROPELLERS COMBINED WITH AN ADVANCED TECHNOLOGY TURBOSHAFT ENGINE

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PERFORMANCE ESTIMATION FOR HIGHLY LOADED SIX AND TEN BLADE PROPELLERS COMBINED WITH AN ADVANCED TECHNOLOGY TURBOSHAFT ENGINE

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SUMMARY

Performance estimations, weights, and scaling laws for the six-blade and ten-blade highly-loaded propellers combined with an advanced turboshaft engine are presented. This data is useful for aircraft mission studies using the turboprop propulsion system. Comparisions are made between the performance of post-1990 technology turboprop propulsion systems and the performance of both a current technology turbofan and a post-1990 technology turbofan.

INTRODUCTION

Recent predicted improvements in the propulsive efficiency of highly loaded propellers at cruise Mach number of 0.8 have led to increased interest (ref. 1) in the use of these devices to propel advanced aircraft. Early studies indicate that, compared to a high-bypass turbofan, turbine-propeller systems offer a potential reduction in direct operating cost of approximately 10 percent and a reduction in aircraft gross weight of approximately 20 percent for long endurance missions. The recent increased emphasis on reduced fuel consumption created by decreasing supplies and increasing cost of fuel, make this concept timely. While near field noise, passenger comfort, and maintenance remain as potential problems, the possible future benefits of this concept have lead to system studies of possible future propeller powered aircraft. These sytem studies require that the weight, scaling, and performance of the propulsion concept be known.

The purpose of this report is to document the predicted performance, scaling, and weight of six-blade and ten-blade highly-loaded propellers (propfans) combined with advanced turboshaft engines (Pratt and Whitney STS 487 of ref. 2) and to compare these results directly with an advanced high-bypass ratio turbofan. Similar results for an eight-blade highly-loaded propeller have been published in reference 3. The approach used herein is the same as that of reference 3. It involves the combination of the predicted propeller data with the engine characteristics to yield the uninstalled performance of the propeller-engine combination in terms identical to those by which turbofan performance characteristics are generally presented.

Since few large commercial propeller-driven aircraft have been designed in the last two decades, computer programs equivalent to those for jet aircraft do not exist for sizing and predicting the performance of turboprop aircraft.

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The present paper provides a means of converting propeller and engine data to a common basis with turbofan engines. The converted data may be used directly in available programs, thus eliminating the need for developing new computer software.

SYMBOLS

C_p	propeller power coefficient, $(P/D^2)/\rho(ND)^3$
C_T	propeller thrust coefficient, $T/(\rho(ND)^2\ D^2)$
D	propeller diameter, m(ft)
g	gravitational constant, 1.0(32.2 ft/s^2)
GR	gearbox gear ratio
HV	fuel lower heat value, 42.717 x 10^6 J/kg (18,400 Btu/lbm)
J	propeller advance ratio, (V/ND)
JC	conversion factor, 1.0(778 ft lbf/Btu)
K_1	constant in equation (10); 0.48371 (.071505) for 6-blade; 0.51136 (.075592) for 10-blade
K_2	constant in equation (11), 1.0203 x 10^{-2} (5.115 x 10^{-3})
K_3	constant in equation (12), 6.3483 x 10^{-2} (0.1044)
M	mass, kg (lbm)
N	propeller revolutions per unit time, revolutions/s
P	engine shaft power, kw (hp)
T	net uninstalled thrust, N (lbf)
TSFC	thrust specific fuel consumption, (kg/hr)/N ((lbm/hr)/lbf)
V	velocity, m/s (ft/s)
W	weight, N (lbf)
W_f	fuel flow, kg/s (lbm/s)
ρ	density, kg/m^3 ($slugs/ft^3$)
η	efficiency

Subscripts:

ENG	engine
G/B	gearbox
jet	jet exhaust
net	net uninstalled
NOM	nominal
o	free stream
ov	overall
p	propulsive
prop	propeller
t	thrust
tip	propeller tip

RESULTS AND DISCUSSION

The Pratt and Whitney STS 487 turboshaft data (ref. 2) was matched with the six-blade and ten-blade propfan data (ref. 4) to calculate the uninstalled net thrust, fuel flow, thrust specific fuel consumption, and overall efficiency of the combined propulsion system. These parameters, and other associated engine and propeller parameters, are obtained as functions of Mach number, altitude, and power setting for both standard and nonstandard day atmospheres.

The propeller is first sized at a selected operating condition. The sizing data required are the design values of Mach number, altitude, shaft horsepower, residual jet thrust, propeller tip speed, power coefficient, and ambient temperature (above a standard day). The approach used is that of reference 3; the details are repeated herein for completeness.

First, the free stream velocity and density are obtained for the known Mach number, altitude and ambient temperature, then the propeller diameter can be obtained as

$$D = \left(\frac{P}{C_p \ \rho (ND)^3} \right)^{1/2} \tag{1}$$

where

$$ND = V_{tip}/\pi \tag{2}$$

The advance ratio (J) is

$$J = \frac{V}{ND} \tag{3}$$

The thrust coefficient C_T can be obtained from tables of reference 4 as a function of Mach number, advanced ratio, and power coefficient. Finally, the propeller thrust can be computed from the thrust coefficient and the results of equations (1) and (2) as

$$T_{prop} = C_T \ \rho (ND)^2 \ D^2 \tag{4}$$

The net thrust can be calculated by adding the residual jet thrust, which is obtained from the engine specifications, to the net propeller thrust

$$T_{net} = T_{prop} + T_{jet} \tag{5}$$

The fuel flow is known from the engine data of reference 2 and, when combined with the results of equation (5), the equivalent thrust specific fuel consumption is calculated as

$$TSFC = W_f/T_{net} \tag{6}$$

Finally, the efficiencies are obtained from the definitions of reference 5 as

$$\eta_{ov} = \frac{T_{net} \ V_o}{W_f(JC)(HV) + V_o^{\ 2}/2g} \tag{7}$$

$$\eta_p = \frac{C_T \ J}{C_p} \tag{8}$$

For the off-design cases, the propeller diameter is fixed from the design computation and the power coefficient is computed from the known engines shaft power, the propeller diameter, the specified propeller rotational tip speed, and equation (2),

$$C_p = \frac{P/D^2}{\rho (ND)^3} \tag{9}$$

Then, the advance ratio J is computed from equation (3) using the velocity corresponding to the specified Mach number, altitude, and temperature. Using these values of C_p and J, and the tables of reference 3, the off-design thrust coefficient C_T can be computed. Equations (4) to (8) are then used to compute the remaining off-design parameters.

The propeller, gearbox, and turboshaft engine weights are estimated using the methods of reference 4 for the propeller and gearbox and reference 2 for the turboshaft engine. Curve fits of the methods described in these references result in the following approximate expressions:

$$W_{prop} = K_1(D)^{2.4998} \left(P/D^2\right)^{0.3036} \left(V_{tip}\right)^{0.3} \tag{10}$$

$$W_{GB}' = K_2 \left(\frac{GR}{8}\right)^{1/2} \left(P/D^2\right) D^3 \tag{11}$$

$$W_{ENG} = K_3(P/D^2)\ D^2 \tag{12}$$

The total uninstalled weight is the sum of equations (10), (11), and (12). It is recommended in reference 5 that this uninstalled weight be mutliplied by 1.3 to account for installation. The nominal engine and propeller sizes can be scaled using the equations of references (2) and (4). (See Appendix A.) It is recommended that the engine scale factor be limited to the range between 0.7 and 1.45. In equations (10), (11), and (12), the power loading (P/D^2) has been expressed separately because, for a given design Mach number and altitude, the power loading (or power coefficient) is held constant as the engine size is scaled to match the required mission thrust. Furthermore, at the design Mach number and altitude, and a constant specified tip speed, a constant power loading (P/D^2) uniquely fixes the advance ratio, the power coefficient, the thrust coefficient, the propulsive efficiency, the overall efficiency, and the thrust specific fuel consumption as the engine size is varied.

SAMPLE CALCULATIONS

This procedure will now be illustrated by some numerical results which assume that the six-blade or ten-blade propellers of reference 4 are matched to the turboshaft engine of reference 2. The tip speed is to be held constant at 244 m/s (800 ft/s). The propellers are to be sized at a Mach number of 0.8 at 11 km (36,089 ft).

The six-blade propeller was sized at a power coefficient of 1.485 or a P/D^2 of 246.9 kw/M^2 (30.75 hp/ft2), and an advance ratio of 3.081. The resulting six-blade propeller diameter for the baseline engine size of 15,238 kw (20,438 hp) at sea-level-static, maximum-power conditions was 4.82 m (15.82 ft). The propeller, as sized for these conditions, was not able to absorb all of the power available from the engine at takeoff. This results in the maximum thrust at takeoff occurring at a reduced power setting of apprxoimately 10008 kw (13421 hp) or about 66 percent of the maximum power available for takeoff. This phenomena, which is also described in reference 3, is demonstrated in figure 1. The total weight of the uninstalled engine, gearbox, and propeller using the nominal 15,238 kw (20,438 hp) engine size is 2683 kg (5910 lbm). The propeller tip speed of 244 m/s (800 ft/s) results in a propeller operating at 965 revolutions per minute with a gearbox ratio of approximately 8.81.

Figure 1 summarizes the performance of the six-blade propfan propulsion system. This figure presents the uninstalled thrust specific fuel consumption as a function of uninstalled net thrust for several different Mach number and altitude combinations.

The ten-blade propeller was also sized at a cruise Mach number of 0.8 at 11 km (36,089 ft). The power coefficient for the ten-blade propeller was selected as 1.779 and the advance ratio was selected as 3.081. The resulting P/D^2 was 295.6 kw/m^2 (36.82 hp/ft^2) at the design condition with a thrust coefficient of 0.4753 and a propulsive efficiency of 0.8233. The resulting ten-blade propeller diameter for the baseline engine size of 15,238 kw (20,438 hp) at sea-level-static maximum power conditions was 4.41 m (14.46 ft). As with the six-blade propeller, the ten-blade propeller was not able to absorb the maximum engine power at sea-level-static conditions and the maximum sea-level-static thrust was achieved at about 67 percent of maximum power (fig. 2). The total weight of the uninstalled engine, gearbox, and propeller using the nominal 15,238 kw (20,438 hp) engine size is 2442 kg (5380 lbm) for the ten-blade propeller. The propeller tip speed of 244 m/s (800 ft/s) results in a propeller operating at 1086 revolutions per minute with a gearbox gear ratio approximately 8.05.

Figure 2 summarizes the performance of the ten-blade propfan propulsion system. This figure presents the uninstalled thrust specific fuel consumption versus uninstalled net thrust for several different Mach number and altitude combinations.

A summary of some design and sea-level-static data for both the six-blade and ten-blade propfan propulsion systems is presented in Table I.

A comparison of the six-bladed turboprop performance, the ten-blade turboprop performance and the performance of the Pratt and Whitney JT9D-25 (ref. 6) is shown in figure 3 through 7. The turboprops have been scaled to match the maximum thrust of the JT9D-25 at a Mach number of 0.8 and a 9.144 km (30,000 ft) altitude. The JT9D-25 engine represents 1965 to 1970 technology while the turboprop gas generator represents post-1990 technology. Data for the post-1990 technology Pratt and Whitney STF-477 turbofan (ref. 7) has also been scaled to the same condition and is shown in figures 3 through 7 to provide a more valid comparison of these systems at an identical level of technology. It can

be seen from figure 6 that the turboprop propulsion systems reduce the cruise specific fuel consumption at a Mach number of 0.8, 30,000 feet by about 27 percent when compared with the 1965 to 1970 technology JT9D-25, and by about 22 percent compared with the post-1990 technology STF-477 turbofan.

A comparison of selected engine performance parameters for the six-blade and ten-blade propfan designs of the present paper and the eight-blade propfan of reference 3 along with the JT9D-25 (ref. 6) and the STF-477 (ref. 7) is shown in Table II. Estimated weight scaling laws for the six-blade and ten-blade turboprop (propfan) propulsion concepts are shown in figure 8. Note that, as discussed in reference 3, the turboprop (propfan) weight increases more rapidly with size than does a typical turbofan. This difference would impose an increased penalty on the turboprop as it scaled upward and would tend to drive aircraft configurations toward a large number of smaller engines rather than a small number of large engines.

A summary of the cruise performance data for the six-blade and ten-blade turboprop (propfan) combined with an advanced turboshaft engine is presented as Appendix B.

CONCLUDING REMARKS

Performance estimation, weight, and scaling laws for six-blade and ten-blade highly-loaded propellers combined with an advanced turboshaft engine have been presented. The data is useful for planned aircraft mission studies using these propulsion systems Comparisons are made between the performance and weight of the post-1990 technology turboprop propulsion systems and the performance and weight of a current technology turbofan and a post-1990 technology turbofan.

At a Mach number of 0.8 and at 9,144 meters altitude, the post-1990 technology ten-blade turboprop and six-blade turboprop produced thrust specific fuel consumption (TSFC) values of approximately 27 percent less than the current technology turbofan and approximately 22 percent less than the post-1990 advanced technology turbofan. These benefits must be measured against the increased system weight, the potential increased maintenance problems, installation drag penalties, noise, and passenger acceptance before any conclusion can be made.

This report furnishes propulsion data to enable the evaluation of air transportation systems using advanced turboprop propulsion systems. The data is presented in a format compatible with existing mission programs.

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APPENDIX A

SCALING LAWS FOR TURBOPROP ENGINE

Engine:

Nominal Engine Length = 2.240 m (7,350 ft)
Nominal Engine Maximum Diameter = 0.914 m (3 ft)
Nominal Engine RPM = 8500
Nominal Engine Takeoff Power = P_{NOM} = 15,23 Mw (20424 hp)

Configuration:

Two spool gas generator with free turbine and third coaxial shaft technology level 1990+ (in service)

Scaling:

Engine Size

$$D_{eng} = \left(\frac{P_{Takeoff}}{P_{NOM}}\right)^{0.5} D_{eng_{NOM}}$$

$$Length_{eng} = \left(\frac{P_{Takeoff}}{P_{NOM}}\right)^{0.43} Length_{eng_{NOM}}$$

Propeller

$$D = D_{NOM} \left(\frac{P_{Takeoff}}{P_{NOM}}\right)^{1/2}$$

Free tubine RPM

$$RPM = RPM_{NOM} \left(\frac{P_{NOM}}{P_{Takeoff}}\right)^{0.5}$$

APPENDIX B

TYPICAL PROPFAN PERFORMANCE OUTPUT

Size Point

	Six-Blade Propeller	Ten-Blade Propeller
Mach Number	0.8	0.8
Altitude	11 km (36089 ft)	11 km (36089 ft)
Temperature	6C (10^oF) above standard	6C (10^oF) above standard
J	3.081	3.081
C_P	1.4851	1.7787
C_T	0.3926	0.4753
η_P	0.8144	0.8233
P/D^2 at cruise	246.9 kw/m^2 (30.746 HP/ft^2)	295.6 kw/m^2 (36.824 HP/ft^2)
Diameter	4.82 m (15.82 ft)	4.40 m (14.46 ft)

Table I.- Propeller Design Information

DESIGN		6-Blade		10 Blade	
Mach number	=	0.80		0.80	
Altitude, km (ft)	=	11.0	(36089)	11.0	(36089)
P, kw (hp)	=	5740.	(7698.8)	5740.	(7698.8)
Propeller Net Thrust, kN (lbf)	=	19.58	(4402.2)	19.80	(4450.4)
Residual Thrust kN (lbf)	=	1.62	(363.2)	1.62	(363.2)
Total Net Thrust kN (lbf)	=	21.20	(4765.4)	21.41	(4813.6)
P/D^2, kw/m^2 (hp/ft^2)	=	246.87	(30.76)	295.58	(36.83)
η_p	=	0.8144		0.8233	
J	=	3.081		3.081	
C_p	=	1.4851		1.7787	
C_T	=	0.3925		0.4753	
W_f, kg/hr (lbm/hr)	=	984.98	(2171.96)	984.98	(2171.96)
TSFC, kg/hr/n (lbm/hr/lbf)	=	0.0499	(0.4934)	0.0456	(0.4512)
η_{ov}	=	0.4002		0.438	
T/P, N/kw (lbf/hp)	=	3.693	(0.619)	3.730	(0.625)
Propeller Diameter, m (ft)	=	4.82	(15.82)	4.408	(14.46)
Number of Blades	=	6		10	
SLS/MAX THRUST					
P, at max. thrust, kw (hp)	=	10.007	(13421)	9260.7	(13421)
maximum available	=	15230.0	(20438.1)	15230.0	(20438.1)
Net Thrust, kN (lbf)	=	93.66	(21055)	89.03	(20015.4)
C_p	=	0.7517		0.9004	
C_T	=	0.5146		0.5841	
J	=	0.0		0.0	
W_f, kg/hr (lbm/hr)	=	1945.0	(4277.9)	1945.0	(4277.9)
T/P, N/kw (lbf/hp)	=	9.361	(1.569)	8.897	(1.4913)
TSFC, kg/hr/N (lbm/hr/lbf)	=	0.0205	(0.2032)	0.0216	(0.2137)
P/D^2, kw/m^2 (hp/ft^2)	=	422.15	(52.60)	515.16	(64.19)

Note: Maximum sea-level-static (SLS) thrust does not occur at maximum engine horsepower because of propeller blade stall.

Table II. Comparison of Selected Engine Parameters

	Engine Thrust - Weight Ratio, Max. Thrust			TSFC	η_{ov}
Engine Type	Sea Level Static	M = 0.3 Sea Level	M = 0.8 9144 m	Cruise Performance, Max. Thrust (M = 0.8, 9144 m altitude)	
(1) 6-Blade Propfan	2.61	2.70	0.83	.472	.423
(2) 8-Blade Propfan	2.65	2.88	0.89	.471	.424
(3) 10-Blade Propfan	2.73	2.95	0.92	.467	.427
(4) Pratt and Whitney JT9D-25 Turbofan	5.50	4.22	1.43	.631	.309
(5) Pratt and Whitney STF-477 Turbofan	6.74	4.89	1.88	.575	.339

Note: All engines are sized to produce net thrust equal to that of the JT9D-25 at M = 0.8, 9144 m altitude.

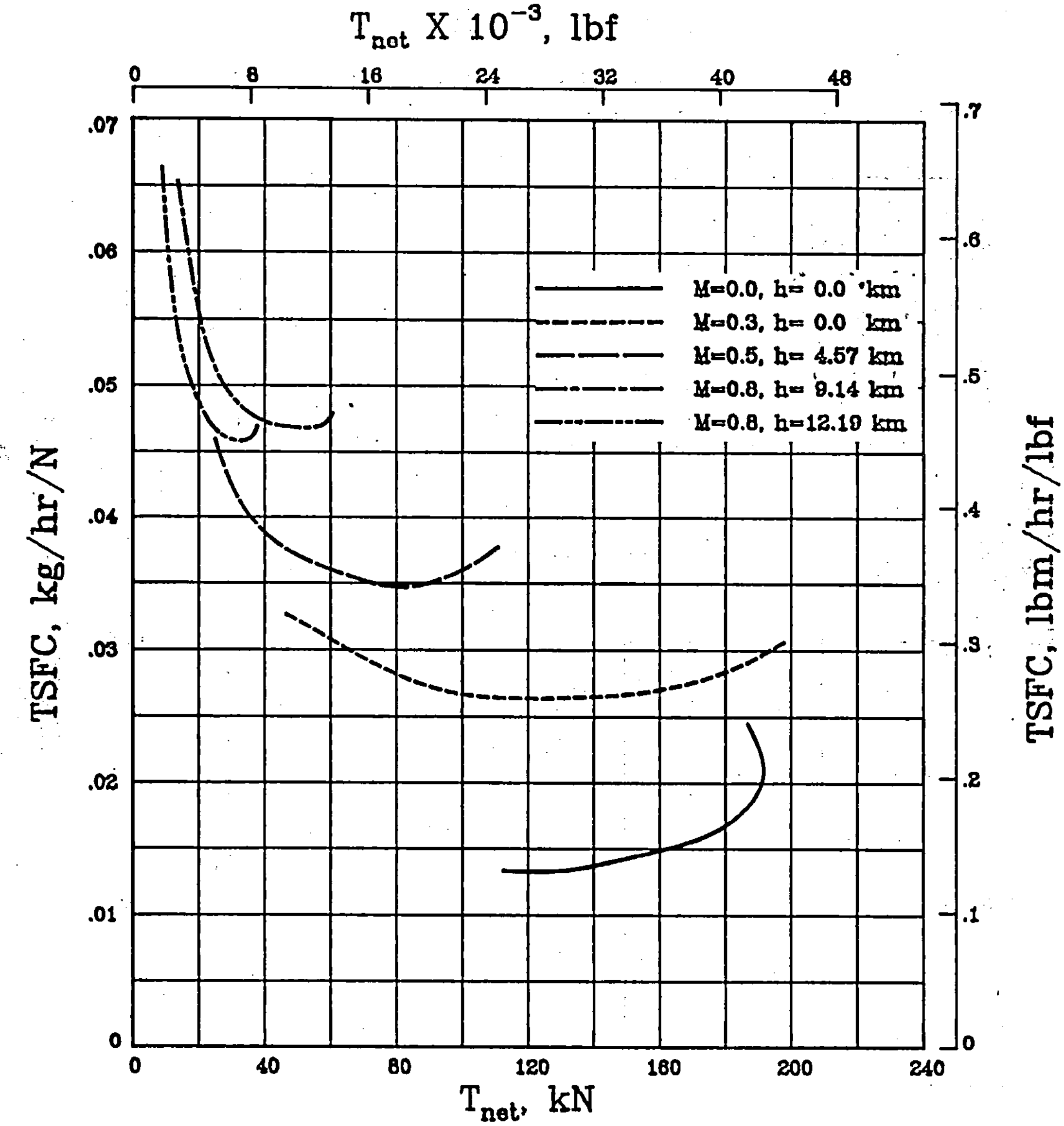

Figure 1. - TSFC versus uninstalled net thrust for a six-blade propfan using a 15238 kilowatt (20438 horsepower) advanced turboshaft study engine in a standard day atmosphere.

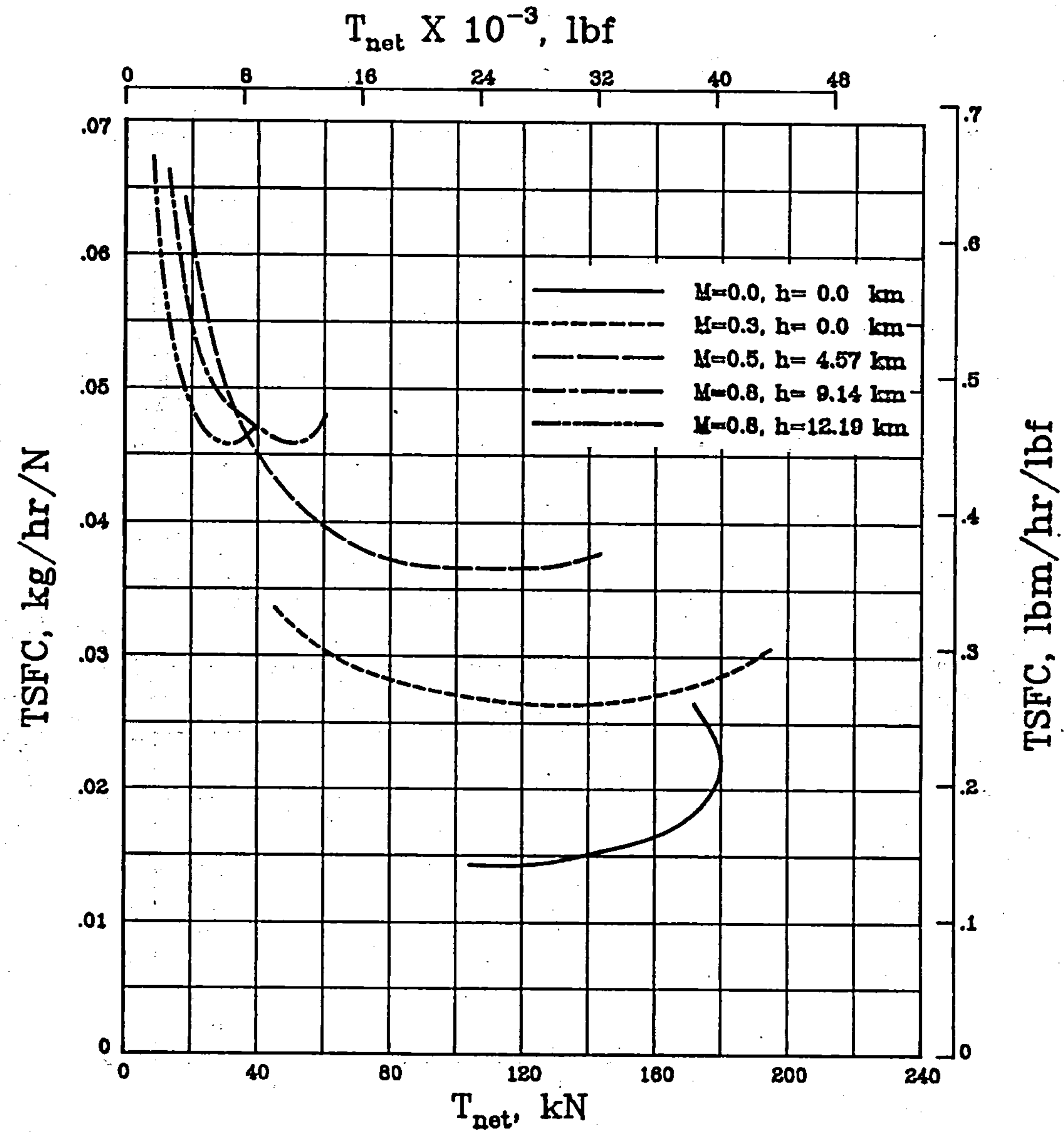

Figure 2. - TSFC versus uninstalled net thrust for a ten-blade propfan using a 15238 kilowatt (20438 horsepower) advanced turboshaft study engine in a standard day atmosphere.

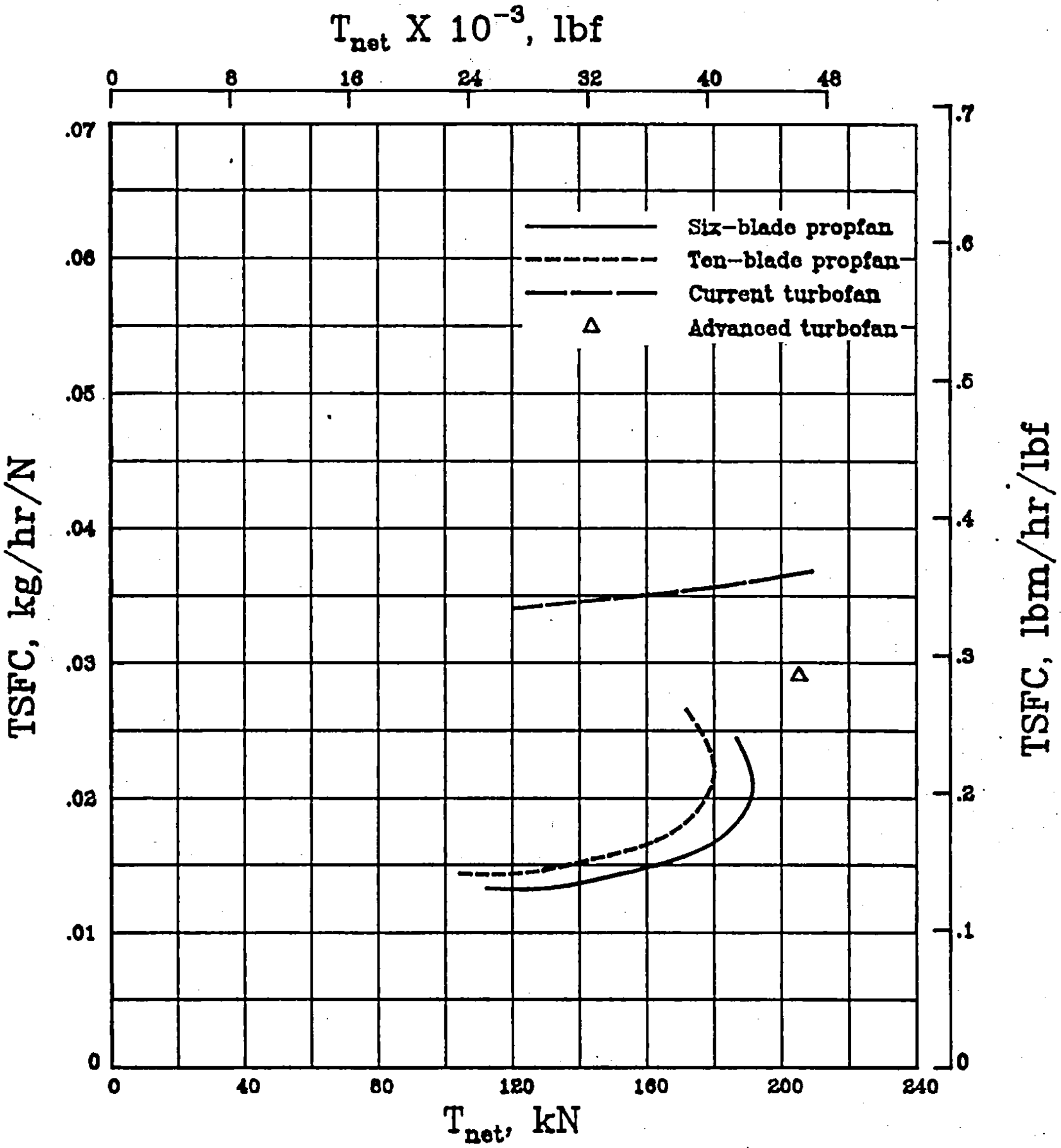

Figure 3. - TSFC versus uninstalled net thrust comparison for the propfan and the turgofan study engines at sea level static, standard day conditions.

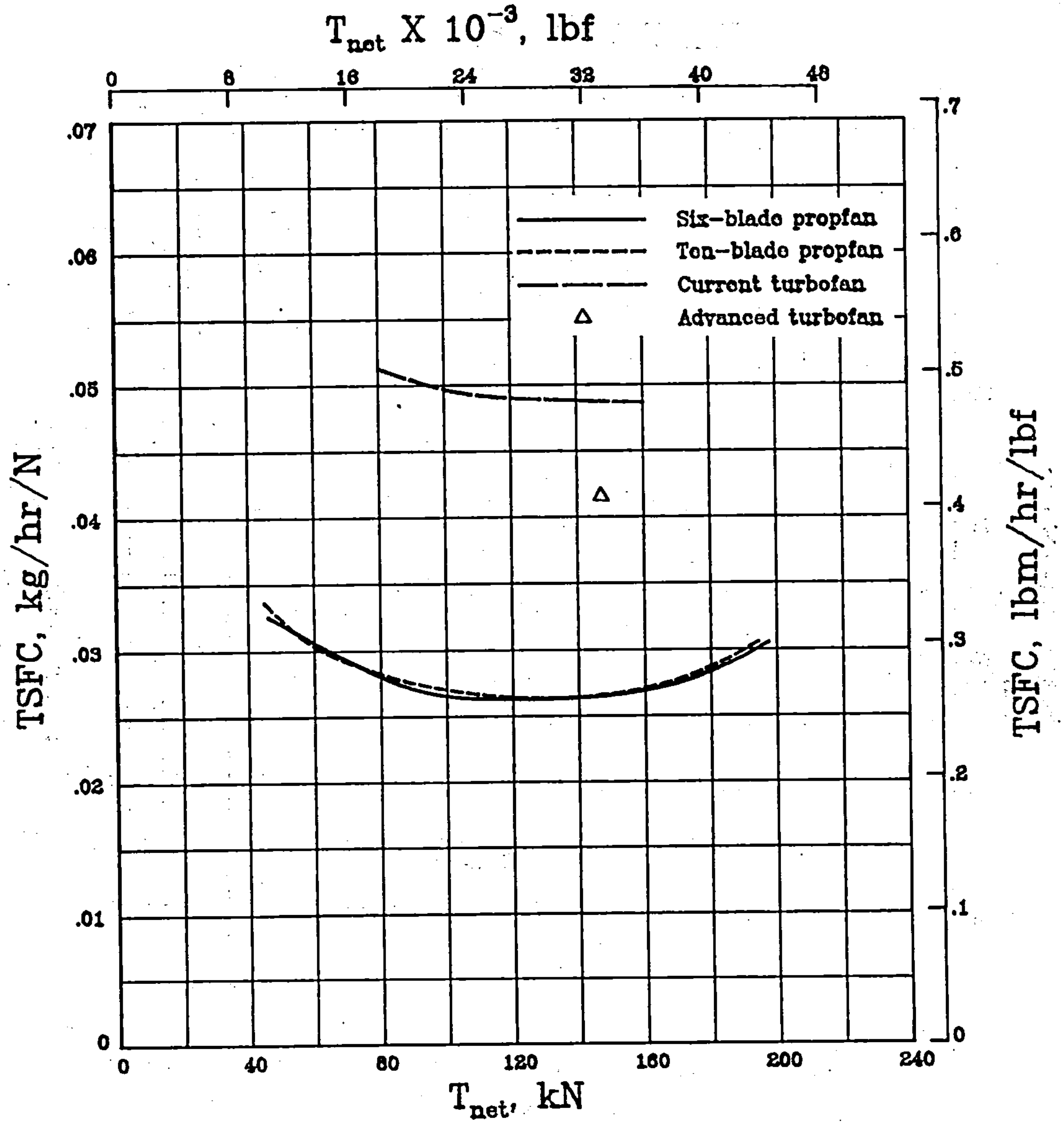

Figure 4. - TSFC versus uninstalled net thrust comparison for the propfan and turgofan study engines at M = 0.3, sea level, standard day conditions.

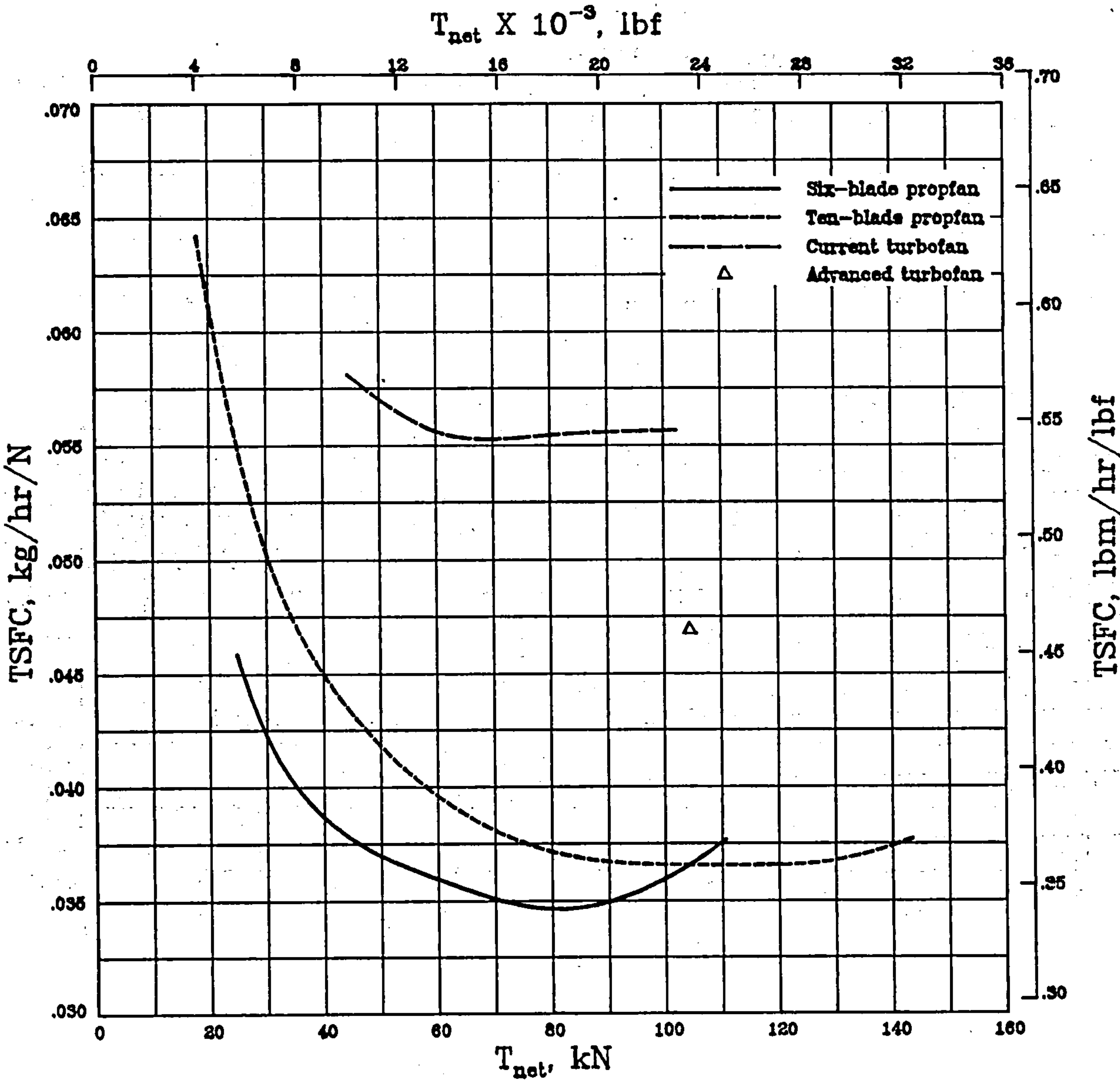

Figure 5. - TSFC versus uninstalled net thrust comparison for the propfan and turbofan study engines at M = 0.5, 4.57 km (15,000 ft), standard day conditions.

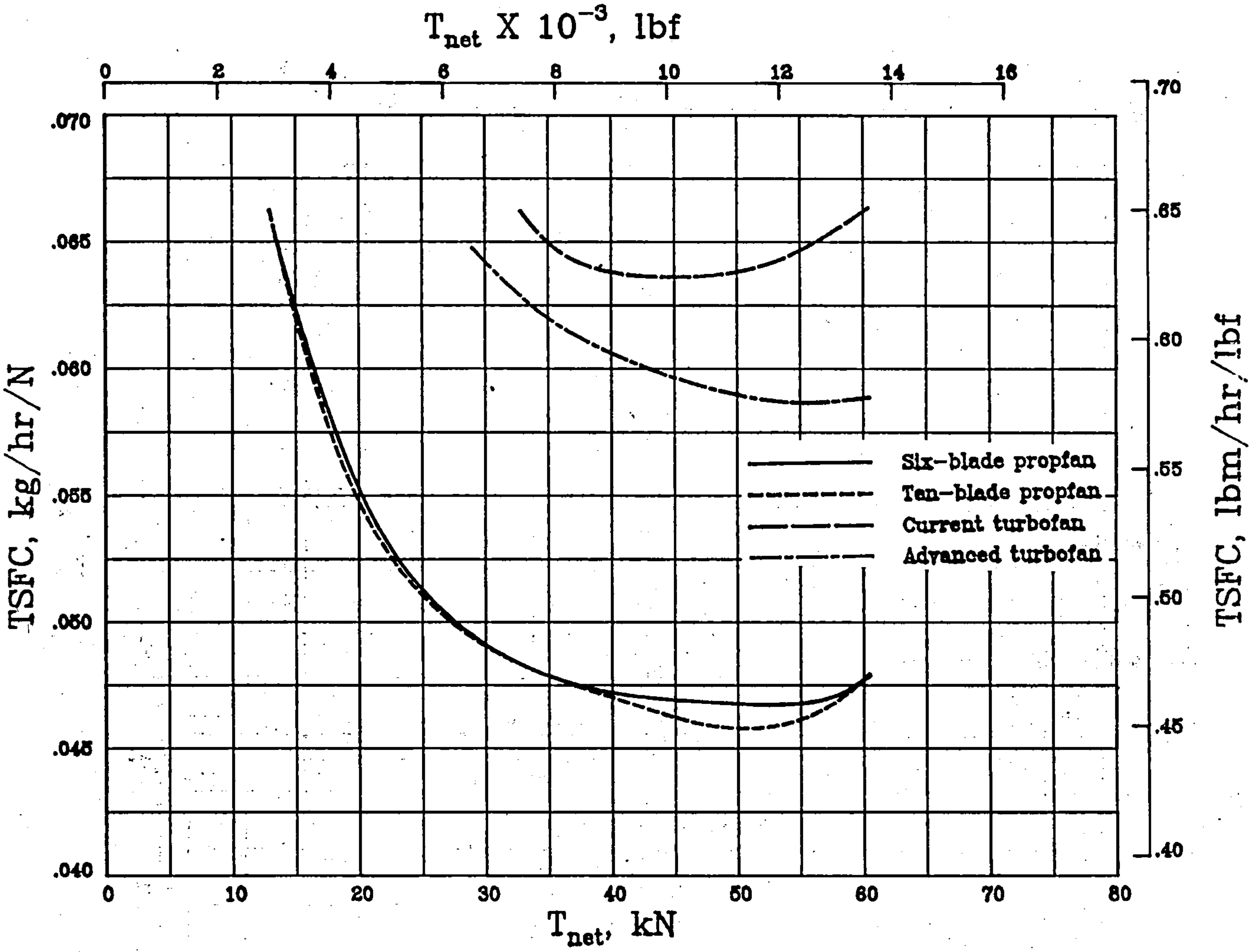

Figure 6. - TSFC versus uninstalled net thrust comparison for the propfan and turbofan study engines at M = 0.8, 9.14 km (30,000 ft) standard day conditions.

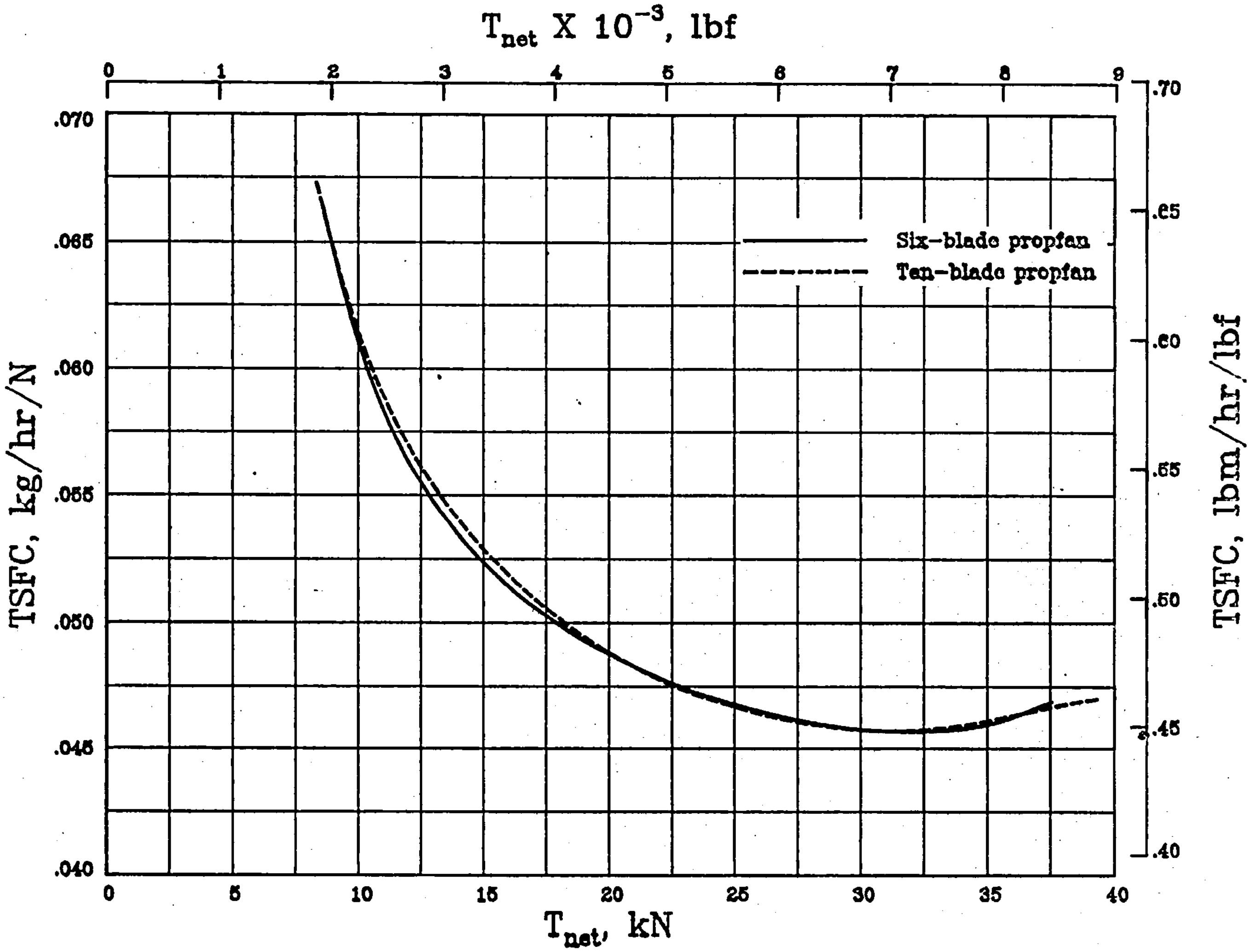

Figure 7. - TSFC versus uninstalled net thrust comparison for the propfan and turbofan study engines at M = 0.8, 12.19 km (40,000 ft) standard day conditions.

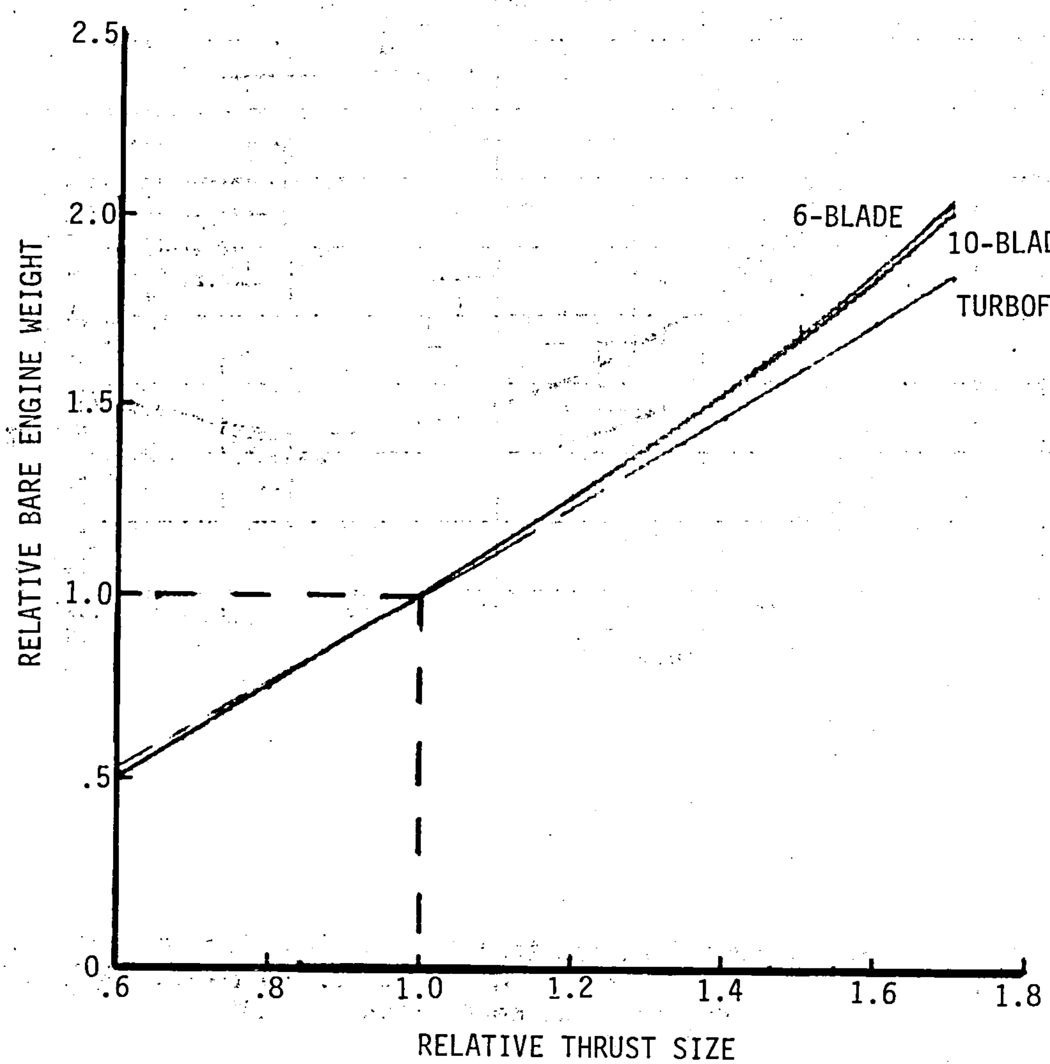

Figure 8. - Estimated weight scaling laws for the six-blade and ten-blade propfan

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16. Abstract

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